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IN-SPACE PRODUCTION OF LARGE SPACE SYSTEMS FROM EXTRATERRESTRIAL MATERIALS – A PROGRAM IMPLEMENTATION MODEL

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16. ABSTRACT

A program implementation model is presented which covers the in-space construction of certain large space systems from extraterrestrial materials. The model includes description of major program elements and subelements and their operational requirements and technology readiness requirements. It provides a structure for future analysis and development.

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TABLE OF CONTENTS

	Page
SUMMARY	1
I. PROGRAM IMPLEMENTATION MODEL	1
A. Introduction	1
B. Description of Program Implementation Model	2
II. PROGRAM REQUIREMENTS FOR AN OPERATIONAL SYSTEM	16
A. Introduction	16
B. General Requirements	18
C. Specific Requirements	23
D. Required Technology Programs	26
III. ASTEROID RESOURCES UTILIZATION FOR THE CONSTRUCTION OF LARGE SPACE SYSTEMS	29
A. Program Element	29
B. Specific Program Requirements	31
IV. DEMONSTRATION SYSTEMS	32
A. Objectives	32
B. Requirements	34
C. Demonstration Systems	36
REFERENCES	42

LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	Program implementation model	3
2.	Transportation systems technology requirements	19
3.	Habitat systems technology requirements	20
4.	Power systems technology requirements	22
5.	Basic capability	33
6.	Logic flow for demonstration program	35
7.	Nonterrestrial construction demonstration model for large space systems	38

LIST OF TABLES

Table	Title	Page
1.	Ground Base	4
2.	Earth Orbital Terminal	5
3.	Lunar Orbit Terminal	7
4.	Lunar Resources Complex	9
5.	L2 Transit Complex	11
6.	Space Manufacturing Facilities	13
7.	Geosynchronous Orbit Complex	16
8.	Program Requirements for Operational Systems	17
9.	General Requirements — Transportation	18
10.	General Requirements — Habitats	21
11.	General Requirements — Power Systems	23
12.	LRC Technology Requirements	24
13.	Specific Requirements — Transition Complex	25
14.	Specific Requirements — Space Manufacturing Facility	26
15.	Required Component Technology Test Beds	27
16.	Required System Technology Demonstration Programs	28
17.	Required Exploration Program	29
18.	Asteroid Resource Complex	30
19.	Specific Program Requirements	31

PREFACE

This report is the result of the author's participation in the activities of a NASA Technical Planning Group, co-located with the 1977 Ames Space Settlements and Industrialization Study Group at Stanford/Palo Alto, California. Participants from universities, industry, and government were involved in studying extraterrestrial material utilization in the construction of large space systems.

The objective of the NASA Technical Planning Group was to arrive at certain planning recommendations for NASA from the work of the study groups.

The 1977 efforts of the study teams as well as prior study efforts resulted in the definition of a large number of individual areas within an extensive and complex program. In order for the NASA Technical Planning Group to proceed in a systematic effort toward planning recommendations, the need existed to present a coherent and comprehensive program model that included all major present and past study areas, established their interrelations, and pointed out voids to be filled in follow-on efforts. This model would also indicate critical requirement issues.

This report attempts to present such a model with brief descriptions of the major program elements, their sub-elements and their technology requirements. In doing this, it is a part of the overall effort and documentation of the NASA Technical Planning Group, which includes required advanced studies, research and development, major test programs, and any social, political, and legal aspects of such a program.

Any future efforts will certainly update this model. As the only one in existence at this time, it is hoped to be a useful point of departure.

TECHNICAL MEMORANDUM 78143

IN-SPACE PRODUCTION OF LARGE SPACE SYSTEMS FROM EXTRATERRESTRIAL MATERIALS – A PROGRAM IMPLEMENTATION MODEL

SUMMARY

Recent studies have indicated that potential economic advantages may be achieved by constructing large space systems from extraterrestrial materials, particularly from lunar materials. To arrive at a thorough understanding of such a complex program and to assist in evaluating options, a program model has been generated describing 7 major program elements and 53 subelements with their specific and technology requirements. This model forms a structure that will provide a rational tool for program orientation and development in any future effort.

I. PROGRAM IMPLEMENTATION MODEL

A. Introduction

Present and past major systems studies involve the definition of major, large space systems for which the material must be transported from the ground for the construction and assembly in space. The studies indicate the major cost impact of transporting the required large quantities of material from Earth and the potential environmental impact of large numbers of heavy lift vehicle launches through the Earth's atmosphere.

A number of NASA sponsored summer studies and independent university efforts [1-6] indicated the possibility that large space systems material delivery and construction from extraterrestrial sources may be of a potential economic and environmental advantage. To approach the question of what technology requirements must be met for an extraterrestrial resources utilization to acquire a state of readiness with sufficient proof data for a potential decision-making process, a program model has been constructed. The extraordinary complexity and the interrelations of a large number of program elements and subelements required this model to visualize the complete program scenario. The following will briefly describe the program model and its major elements.

B. Description of Program Implementation Model

According to present and past summer studies [1-6], the extraterrestrial large space system implementation program (Fig. 1) consists of the following major program elements:

1. Ground Base (GB)

2. Earth Orbital Terminal (EOT)

3. Lunar Orbital Terminal (LOT)

4. L2 Transit Complex (TC)

5. Space Manufacturing Facility (SMF)

6. Geosynchronous Orbit Complex (GSOC)

7. Asteroid Resources Complex (ARC).

The latter program element is disucssed only to present a complete program. The main emphasis will be placed on the lunar resources utilization. Each program element involves a family of required activities to be performed and a set of program subelements which enables these activities to be carried out and supports them.

1. Ground Base (GB). Here, all program implementation activities are centrally controlled and managed (Table 1). The model presented does not include any direct large space system related operational activities. However, the overall management of the various extraterrestrial activities and facilities

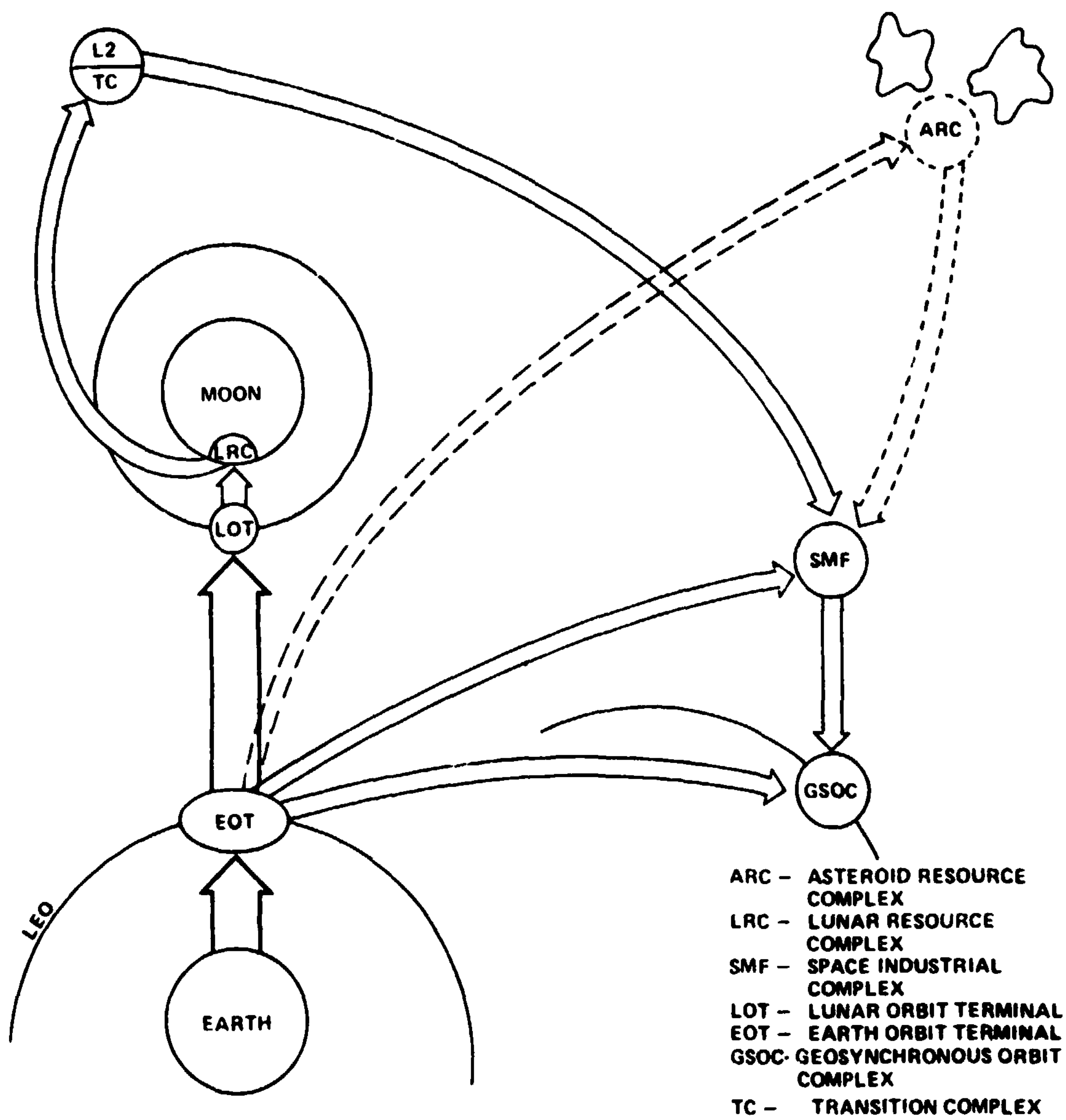

Figure 1. Program implementation model.

TABLE 1. GROUND BASE (GB)

Required Activities
• All large space systems related activities as being defined in related systems studies
Plus
• Overall space facilities management and communication
• Overall personnel management for all space arenas involved
• Total logistics and emergency management
• Accounting
Program Subelements
To be defined by proposed system studies

and the extensive communication network required for operational program flow is located here. The management and control of up to 6000 personnel in all space arenas involving the total logistics, transportation, status, and emergency operations management are located at GB. And, finally, since this is a major industrial investment operation, an accounting and business management system controls the inputs and outputs of the total enterprise.

2. Earth Orbital Terminal (EOT). This terminal is the main throughfare for all required cargo and personnel traffic for the program buildup phase and implementation (Table 2). Here, traffic loops from the ground, from LOT, SMF, and from the GSOC will be handled, interfaced, and scheduled.

A sizeable personnel testing and training facility will establish and maintain the personnel force in space with qualified people throughout the program. Cargo to LOT, SMF, and GSOC must be stored and transferred, and personnel

TABLE 2. EARTH ORBITAL TERMINAL (EOT)

Required Activities
• Personnel and cargo reception from Earth, LOT, SMF, GSOC
• Personnel testing and training
• Personnel habitation and cargo storage
• Control and management of operations and local traffic
• Control of launch operations to LOT, SMF, GSOC
• Personnel and cargo transfer from a LOT
• Maintenance
• Habitat checkout
Program Subelements
• Earth-LEO transportation (P& C)
• LEO staging and cargo base
• LEO habitat base
• LEO operations control station
• LEO launch control station
• LEO equipment and operations
• LEO local transportation
• LEO power

of 50 to 100 individuals in residence and in transit must be housed. In addition, in and out-going, as well as local traffic, requires management and launch control. A major operation is the checkout and maintenance of local and in-transit facilities or their elements. Particularly, space habitats to be installed at the LOT, LRC, and SMF will undergo extensive qualification testing in EOT.

The program subelements of the EOT are:

a. Earth to low Earth orbit (LEO) transportation for both personnel and heavy cargo.

b. Staging and cargo base for docking and exchanging payloads between transportation systems.

c. Habitat.

d. Operations control station for EOT.

e. Launch control station for outgoing vehicles.

f. A multitude of equipment to perform required operations to be defined by system studies.

g. Local transportation for cargo and personnel between stations and vehicles.

h. Propellant storage facility.

i. A power station for electric energy required for all facilities and operations.

3. Lunar Orbit Terminal (LOT). This terminal is the main throughfare for all lunar surface personnel and equipment as well as for cargo and personnel for the L2-TC (Table 3). This involves docking and launch operations for flights to and from EOT, LRC, and TC, the provisions of cargo storage and transfer of cargo between different vehicles, the control of all launch operations, and the overall control and management of operations, maintenance, and local traffic.

TABLE 3. LUNAR ORBIT TERMINAL (LOT)

Required Activities
• Personnel and cargo reception from EOT and L2
• Personnel habitation and cargo storage
• Control and management of operations and local traffic
• Control of launch operations to EOT and LRC
• Personnel and cargo transfer from EOT to LRC, L2, SMF
• Maintenance
Program Subelements
• LEO-LOT transportation (P& C)
• LOT staging and cargo base
• LOT habitat base
• LOT operational control station
• Launch control station
• LOT equipment and operations
• LOT local transportation
• LOT power

The program subelements of the LOT are:

a. EOT-LOT transportation for both personnel and cargo.

b. Staging and cargo base for docking and exchanging payloads between transport systems.

c. Habitats.

d. Operations control station for LOT.

e. Launch control station for outgoing vehicles.

f. Propellant storage facility.

g. A multitude of equipment to perform required operations to be defined by system studies.

h. Local transportation for cargo and personnel between stations and vehicles.

i. A power station for electric energy required for all facilities and operations.

4. Lunar Resources Complex (LRC). This complex is the source of all material required at the SMF to construct and assemble large space systems (Table 4). Here, incoming equipment, logistics, and personnel from EOT via LOT are received. Cargo is moved, stored, and deployed; personnel is provided with habitats. All flight operations and surface transportation for personnel and cargo is controlled and managed.

Large scale strip mining operations of up to 1 500 000 tons per year are performed involving mining, drilling, scraping, loading, and other operations, including equipment maintenance. A major LRC operation is the continuous cargo transfer to the SMF via the TC at L2. In addition, periodic personnel transfer to these points is required for maintenance and logistics.

A personnel testing and training program is also part of the lunar surface activity requirements.

TABLE 4. LUNAR RESOURCES COMPLEX (LRC)

Required Activities

- Personnel and cargo reception from LOT
- Personnel habitation and cargo storage
- Control and management of operations and surface traffic
- Personnel and cargo surface transportation
- Surface operations — mining, drilling, scraping, mucking, and loading
  — surveying, marking, and analyzing
- Maintenance
- Personnel and cargo transfer to L2 and LOT
- Cargo and personnel launch to L2 and LOT
- Personnel testing and training

Program Subelements

- LOT-LRC transportation (P& C)
- LRC staging and cargo base
- LRC habitat base
- LRC operational control station
- LRC mining subcomplexes
- LRC equipment and operations
- LRC materials conditioning station
- LRC ground transportation
- LRC launch facilities and operations
- Power systems

The program subelements of the LRC are:

a. LOT-LRC transportation for both personnel and cargo.

b. Staging and cargo base for refitting of vehicles and unloading and storing equipment and supplies.

c. Habitats.

d. Operational control station for all lunar operations.

e. A number of mining subcomplexes depending on the selenographic distribution of required ground materials.

f. Strip and deep mining equipment, and surveying and prospecting equipment.

g. Raw material conditioning and processing station.

h. A fleet of surface transporters for cargo and personnel.

i. Launch facilities for cargo and personnel transport to LOT, TC, and SMF.

j. Propellants storage facility.

k. Power stations for electric energy required for all facilities and operations.

5. L2 Transit Complex (TC). This complex forms an interim station for a ballistic trajectory supply line to the SMF (Table 5). The L2 area contains equipment and facilities that receive cargo from the LRC. After certain cargo masses have accumulated, they are then transfered to the SMF.

The main requirement of this complex is the interception of free-flying compact cargo packets arriving from LRC in a continuous sequence. A superior navigation, attitude control, and stationkeeping capability is required for a sustained interceptor operation. Periodic personnel arriving for maintenance must be safely accommodated and provided with local transportation during their stay time. Facilities and cargo transfer operations require control and management.

TABLE 5. L2 TRANSIT COMPLEX (TC)

Required Activities

- Cargo and personnel reception from LRC
- Personnel habitation
- Control of LRC and SMF launch operations
- Cargo transfer from reception to launch
- Local transportation

Program Subelements

- LRC-TP transportation (P&C)
- TC cargo receiving terminal
- TC staging and cargo base
- TC habitat base
- TC operational control station
- TC propellant storage
- TC equipment and operations
- TC launch facility and operations
- TC local transportation
- TC power station

Personnel return launches and cargo transport launch operations to SMF require control activities.

The program subelements of TC are:

a. LRC to TC transportation for cargo and personnel.

b. Cargo interceptor ("catcher") facility.

c. Staging and docking base for personnel transporter.

d. Cargo accumulation facility.

e. Temporary habitat.

f. Operations control station (manned or automated) for interceptor and launch control.

g. Various auxiliary equipment to be defined by system studies.

h. Launch control facility for LRC and SFM transports.

i. Temporary local transportation for facility maintenance.

j. Power station for required electrical energy.

k. Propellant storage facility.

6. Space Manufacturing Facility (SMF). A line of large space systems will be constructed and assembled from material received from the LRC via the L2-TC (Table 6). This requires receiving of cargo from EOT (supplemental material to the lunar material) and L2-TC, as well as personnel from EOT. Personnel habitation must be provided for an assembly crew of up to 6000 resident people and a contingency for transit personnel to be defined. Major control, management, and government functions covering operations, traffic, and population relations have to be carried out.

Launch operations control for transfer flights of produced large space systems to GSOC and of personnel flights to EOT are required. Local mobility for personnel and cargo must be provided.

TABLE 6. SPACE MANUFACTURING FACILITIES (SMF)

Required Activities

- Personnel and cargo reception from EOT and L2
- Personnel habitation
- Control and management of operations and local traffic
- Control of launch operations to GSOC and EOT
- Personnel and cargo local transport
- Cargo storage
- Chemical materials processing
- Metallurgical manufacturing
- Photovoltaic blanket manufacturing
- Component manufacturing
- Production control
- Assembly and test

Program Subelements

- Local transportation
- LEO-SMF transportation (P&C)
- TC-SMF transportation (P&C)
- SMF cargo receiving station
- SMF staging and cargo base
- SMF habitat base
- SMF operational control station
- SMF chemical processing facility
- SMF metallurgical manufacturing facility
- SMF silicon photovoltaic manufacturing facility
- SMF component manufacturing facility

TABLE 6. (Concluded)

• SMF production control station
• SMF assembly complex
• SMF test station
• SMF equipment and operations
• SMF local transportation
• Power systems

Incoming material and produced hardware elements will require storage. Major operations for the production of large space systems involve chemical materials processing, the manufacturing of hardware building blocks and elements, and the mass production of photovoltaic blankets and various components. This requires close production control, management, and quality control activities. Component assembly checkout and testing requires extensive facilities, equipment, and again management activities. A local transportation fleet for both cargo and personnel is required.

The program subelements of the SMF are:

a. EOT-SMF transportation for cargo (initial facilities buildup and maintenance) and personnel.

b. TC-SMF transportation for cargo (large space systems material).

c. Cargo and personnel receiving station.

d Vehicle and cargo docking station.

e. Habitats.

f. Operations control station.

g. Chemical processing facility.

h. Metallurgical manufacturing facility.

i. Silicon photovoltaic manufacturing facility.

j. Component manufacturing facility.

k. Production control station.

l. Assembly complex.

m. Test station.

n. Various equipment to be defined by system studies.

o. Local transportation for cargo and personnel.

p. Power station for electric energy required.

7. Geosynchronous Orbit Complex (GSOC). This complex is the final location of the operational large space systems (Table 7). Here, the final completion of the large space system assembly takes place utilizing supplementary system elements manufactured from terrestrial sources.

This complex will be defined essentially by special studies. The extraterrestrial resources utilization requires the following additional activities:

a. Reception and positioning of prefinished large space systems from SMF and of terrestrial components from EOT.

b. Final assembly of terrestrial components and integration of the complete large space system.

The program subelement listed here for GSOC is SMF-GSOC transportation (of large space system). Other subelements will be defined in special studies.

TABLE 7. GEOSYNCHRONOUS ORBIT COMPLEX (GSOC)

This complex will be defined essentially by special studies of various large space systems. Extraterrestrial resources utilization requires the following additional activities and subprogram elements:
Required Activities
• Reception of product cargo (large space system) from SMF
• Integration and final assembly of terrestrial components of the large space system
Program Subelements
• SMF-GSOC transportation (C)

II. PROGRAM REQUIREMENTS FOR AN OPERATIONAL SYSTEM

A. Introduction

This section covers presently envisioned program requirements for operational extraterrestrial resources delivery systems (Table 8). The in-space construction of large space systems is not included. Recommended system and economic analyses studies will update the preliminary requirements listed in this report.

The requirements presented are divided into two parts. The general requirements are those which are applicable throughout the entire program scenario. They include transportation, habitat, and power systems. The specific requirements are those which are applicable only to certain elements of the program scenario. They include the LRC, TC, and the SMF.

TABLE 8. PROGRAM REQUIREMENTS FOR OPERATIONAL SYSTEMS

General Requirements (Applicable to Total Program)
• Transportation
• Habitats
• Power systems
Specific Requirements (Applicable to Specific Program Elements)
• LRC
• TC
• SMF
• (ARC)
Required Technology Programs
• Components
• Systems
• Exploration

The resulting required technology programs are divided into the following areas of coverage:

1. Component technology test beds and system technology demonstrations for extraterrestrial resources extraction and delivery.

2. Necessary exploratory efforts, prospecting, and surveying.

B. General Requirements

1. Transportation. There are 19 different transportation requirements within the extraterrestrial materials utilization program (Table 9 and Fig. 2). (If asteroid resources would be included, this number increases to 25 requirements.) It appears necessary to consider common elements to the maximum extent. This may be quite a challenge due to the many different requirements but would be a potential move toward maximum economy. This commonality approach should involve all major transportation system elements such as propulsion, structures, guidance and control, power, and payload interfaces. Particular attention must be paid toward commonality and standardization of personnel transport modes and local transportation systems. An overall transportation operations analysis must be undertaken to optimize this total space mobility system.

TABLE 9. GENERAL REQUIREMENTS — TRANSPORTATION

Space Transportation	Cargo per Flight	Annual Cargo	Annual Personnel
Earth — EOT	220 tons	26 400 tons	1 650
EOT — LOT	175 tons	175 tons	48
LOT — LRC	TBD	175 tons	48
LRC — TC	Continuous	< 1 500 000 tons	15 flights @ 5 per flight
EOT — SMF	Continuous	TBD	1500
TC — SMF	3 000	< 1 500 000 tons	
SMF — GSOC	100 000 tons	< 1 500 000 tons	
Local	**Cargo**	**Personnel**	**Range**
EOT	TBD	2	10^2 km
LOT	TBD	2	10^3 km
LRC	TBD	2	10^2 km
TC	TBD	2	10^3 km
SMF	TBD	2	10^3 km
GSOC	TBD	2	10^2 km

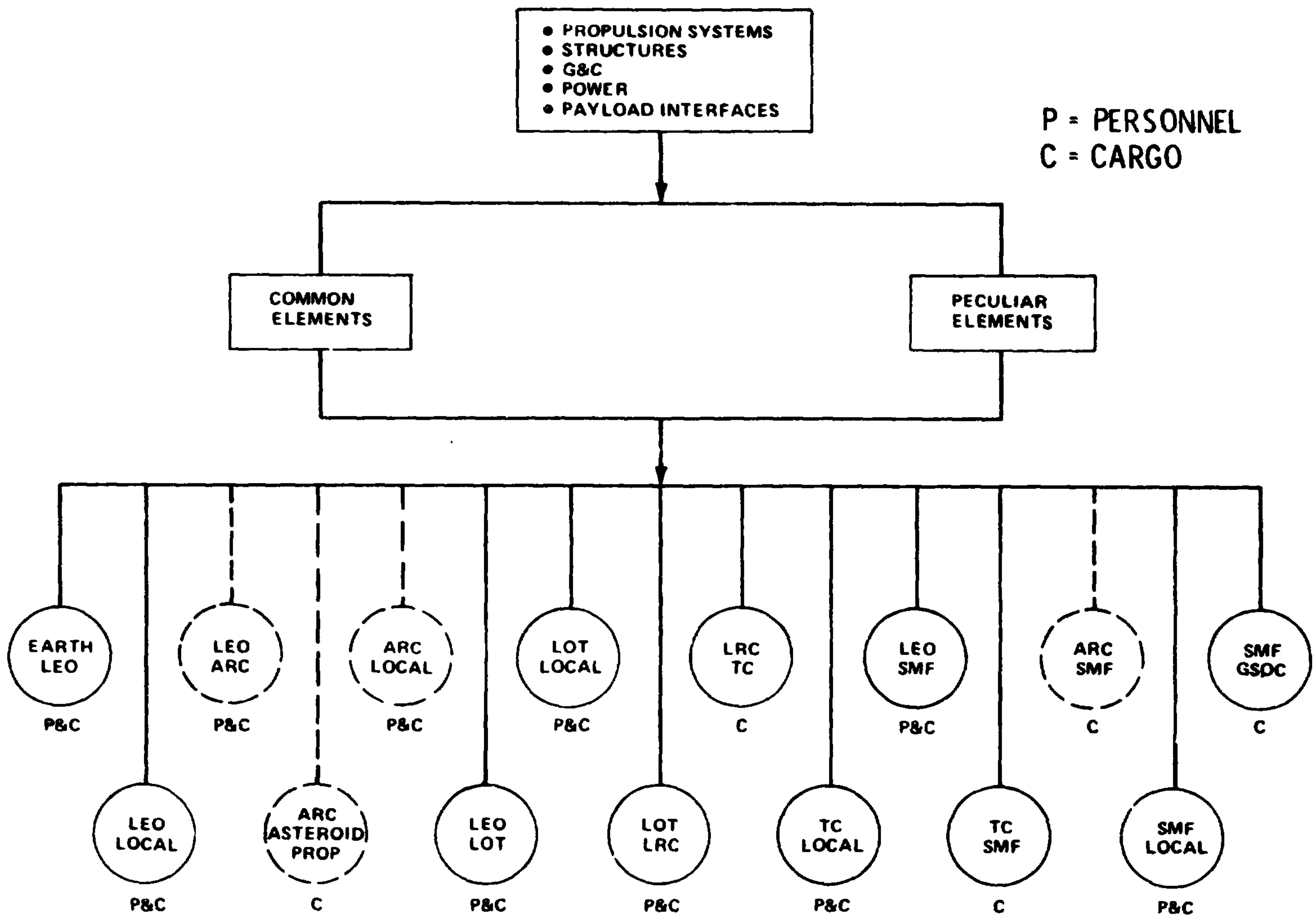

Figure 2. Transportation systems technology requirements.

2. Habitats. There are six different habitat requirements within the extraterrestrial materials utilization program (Fig. 3 and Table 10). (If asteroid resources would be included, this number increases to seven requirements.)

The description and application of the common elements in the various required space transportation systems applies also to the habitats. This commonality approach should involve all major habitat system elements such as life support and ecological systems, structures, attitude control and stationkeeping, and power and thermal control. An overall habitat systems analysis and design study must be undertaken to optimize this total space habitation system. While the specific study on "closed ecological systems" decided that this development could not be accomplished within the development time frame of the program and is not required for technical feasibility, it would be rather

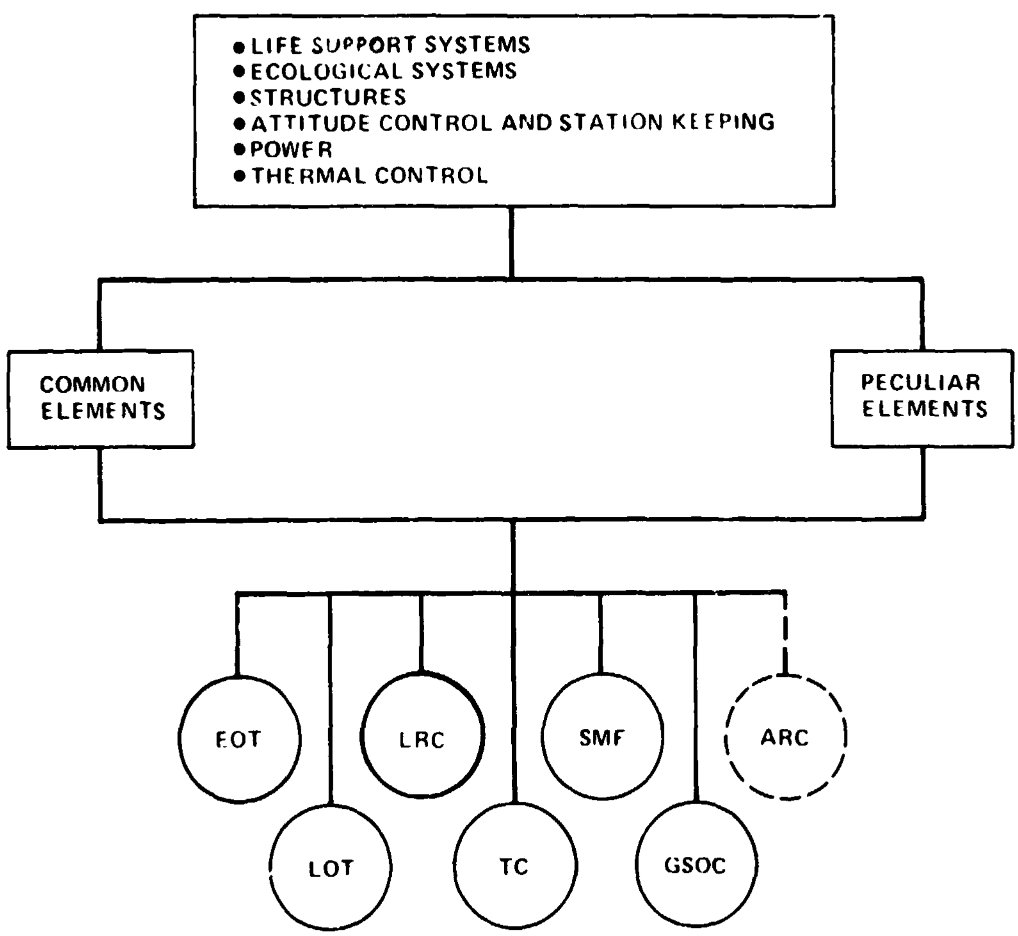

Figure 3. Habitat systems technology requirements.

TABLE 10. GENERAL REQUIREMENTS — HABITATS

Habitat Systems	Population	Function
EOT habitat	50 to 100	Main traffic control terminal
LOT habitat	5 to 10	Transit control Earth — Moon
LRC habitat	50 to 100	Mining, material processing
TC habitat	5 (temporary)	TC maintenance and control
SMF habitat	< 6500	Large space system production
GSOC habitat	To be defined by system studies	

timely to develop a closed ecosystem model for potentially improved systems economy. A step-wise approach is recommended through various levels of details where subprograms covering both biological and physico-chemical systems can be considered.

The building blocks of such a model would encompass management systems for atmosphere, water, food, waste, energy, and space environment. This model then can be used to perform parametric analyses and optimizations if coupled to an appropriate experimental program which by definition is required to be of a long duration, covering several generations of biological samples.

3. Power Systems. The ultimate selection and sizing of the required power systems and stations must be the result of extensive system analyses studies. Preliminary requirements, regardless of the power system options, are given in Figure 4 and Table 11.

Again, an attempt needs to be made for maximum commonality among the various power system elements to stay within reasonable economic boundaries.

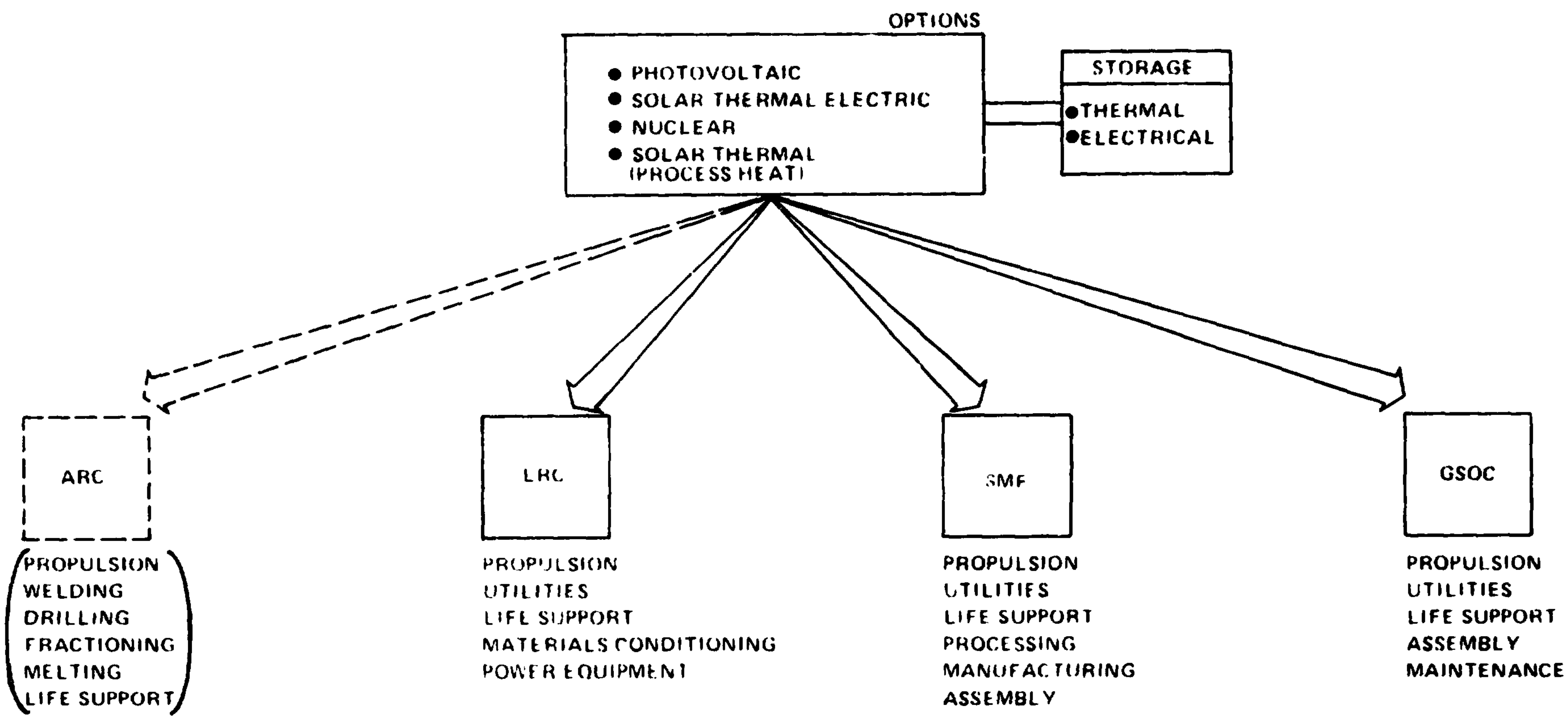

Figure 4. Power systems technology requirements.

TABLE 11. GENERAL REQUIREMENTS – POWER SYSTEMS

Power Systems	Demonstration Capacity (kW)	Operational Capacity (kW)
EOT	50 to 100	100 to 200
LOT	10 to 20	10 to 50
LRC (with mass driver)	30 000 to 60 000	200 000 to 250 000
TC	1000 to 2000	3000 to 5000
SMF	300 000 to 500 000	1 500 000 to 3 000 000
Transport		
Chemical	(Insufficient data)	(Insufficient data)
Mass driver	3000 to 5000	3000 to 5000
Other	(Insufficient data)	(Insufficient data)

C. Specific Requirements

1. Lunar Resources Complex (LRC). A detailed lunar materials survey is required that will show specific selenographical materials distributions and characteristics from the surface to as much depth below the surface as possible (Table 12). This is necessary for lunar operational site selections and for operational planning (strip mining versus deep excavation material extraction). The required equipment for moving up to 10^9 kg mass of lunar raw material per year must provide for all applicable operations like excavation, drilling, grading, screening, mucking, and loading. Auxiliary equipment for lunar ground stabilization, material conveyance, continued ground material analysis, and mass flow measurements is required.

TABLE 12. LRC TECHNOLOGY REQUIREMENTS

Exploration	
Construction of:	
• Landing and launch sites	
• Roads and Bridges	
Operation of:	
• Mining areas	
• Material delivery areas	
• Spoil areas	
Activities Required	**Equipment Line-Up (Spread)[a]**
• Grading	• Power shovels
• Scraping	• Motor scrapers
• Shoveling	• Bulldozers
• Crushing	• Motor graders
• Screening	• Conveyors
• Drilling	
• Mucking	

a. Big, fast, lightweight, powerful, automated with quality control.

2. Transition Complex (TC). This is the least defined major program element. The requirement of intercepting a steady mass stream of approximately 50 kgs^{-1} appears to be unresolved even in the conceptual phase. Part of this deficiency is based on the postulated required lunar launch accuracy which is within millimeters per second of velocity and seconds of arc in its vectors. Thus, the requirements for solving the problems of the payload interceptor ("mass catcher") lie in its physical concept, guidance and control, stationkeeping and changing, and dynamic stability (Table 13). An exhaustive design and operational analysis is required before any technology work can be initiated. This should include the number and sequencing of interceptors and safety aspects of maintenance personnel.

TABLE 13. SPECIFIC REQUIREMENTS — TRANSITION COMPLEX

Payload interceptor
Payload — interceptor interfaces
• Physical concept
• Guidance and control
• Attitude and stationkeeping
• Dynamic stability
Interceptor sequencing, exchange
Safety for maintenance personnel

3. Space Manufacturing Facility (SMF). The SMF must receive, store, move, and process the quantities of lunar materials given in Table 14. The form of packaging and transfer of that cargo from TC has not been very well defined.

Since SMF is a major industrial space facility for the production of large space systems, a detailed production operational system analysis and optimization is required covering the total process from feedstock reception to qualified product output. Obviously, a high degree of automation of this process is required.

TABLE 14. SPECIFIC REQUIREMENTS – SPACE MANUFACTURING FACILITY

Material	Total Mass (%)	Mass (kt) (maximum)
Propellant mass	20	300
Oxygen	16.5	247
Silicon	10.5	157
Fiberglass	2	30
Aluminum	7.5	113
Iron	4.5	68
Titanium	3	45
Slag (for shielding)	36	540
Total		1500

D. Required Technology Programs

1. Required Component Technology Test Beds. Program components are considered that constitute major critical areas within the program elements (Table 15). It is assumed that an extensive research and development program covering ground and space borne technology advancement experiments and verification activities will be conducted before the technology readiness planning date. Within this time period, five technology test bed programs will verify and update integrated system elements (components) in preparation for larger

TABLE 15. REQUIRED COMPONENT TECHNOLOGY TEST BEDS

Component Technology Test Beds	$ \$ \times 10^6 $
Material process SMF	100 to 200
Space manufacturing system	200 to 500
High efficiency OTV engine[a]	(200 to 500)
Construction systems[a]	(200 to 300)
Long-term habitats[a]	(200 to 300)
Mass catcher	200 to 300
Total	500 to 1000
	(600 to 1100)

a. To be covered by special studies.

scale systems demonstration programs. Attention is drawn to those technology test bed requirements that are peculiar to the extraterrestrial resources utilization. It is assumed that the ongoing and planned large space systems activities will cover all areas peculiar to those systems.

2. Required System Technology Demonstration Programs. In addition to implementing required technology advancements through extensive technology test bed operations, a larger scale system technology demonstration program is required which has the objective of demonstrating the capabilities called for by the operational program (Table 16). Again, attention is drawn to those systems that are assumed to be covered by the ongoing and planned large space systems activities.

For details of this program see Section IV.

TABLE 16. REQUIRED SYSTEM TECHNOLOGY DEMONSTRATION PROGRAMS

System Technology Demonstration Program	$\$ \times 10^6$
Power demonstration[a]	(500 to 1000)
Lunar launcher	500 to 1000
Mass catcher	500 to 1000
High efficiency OTV engine[a]	(500 to 1000)
Material processing SMF	1000 to 2000
Construction systems[a]	Included in other programs listed here
Lunar power systems	200 to 400
Long-term habitats	(2000 to 3000)
Manufacturing systems	500 to 1000
Total	2700 to 5400
	(5700 to 10 400)

a. To be covered by special studies.

3. Required Exploration Program. A thorough investigation of type and distribution of lunar surface materials down to a reasonable depth is required for any lunar resources utilization program.

The first requirement will be for a sensor equipped polar Orbiter that would provide a detailed selenological survey and mapping with regard to specific materials, their chemical characteristics, and concentrations across the entire lunar surface and subsurface.

Based on the results of these measurements and the recognition of specific promising areas, a number of lunar surface prospector missions are required that explore these selected areas through surface and depth sample analyses.

Another program aspect which requires exploration is the area around the lunar trailing libration point L5 which is a potential candidate location for the SMF. This weak gravitational well may have accumulated finely dispersed particles which may be harmful for operations being conducted there. An explorer satellite orbiting within this area will provide measurements on any size particle distribution. For details of this program see Table 17.

TABLE 17. REQUIRED EXPLORATION PROGRAM

Exploration Program	$\$ \times 10^6$
Lunar polar Orbiter	300
Libration point exploration	300
Lunar prospector	TBD

III. ASTEROID RESOURCES UTILIZATION FOR THE CONSTRUCTION OF LARGE SPACE SYSTEMS[1]

A. Program Element

The ARC is envisioned to be a long duration manned spacecraft flying formation with a selected asteroid to prepare it for a transfer trajectory which would insert it into a desired Earth orbit for utilization at the SMF. The propulsive energy is expected to be derived from solar electric energy used to consume a portion of the asteroid mass.

1. Asteroid resources utilization is covered here for completeness only. It lacks sufficient definition throughout its program structure and, therefore, is considered a remote concept at this time, compared with the lunar resources utilization which is the main subject of this model.

The required activities and the program subelements are given in Table 18. The activities involve asteroid despinning and docking of propulsion and guidance and control systems. The program subelements of the ARC are:

a. LEO-ARC transportation of personnel and cargo.

b. Habitat spacecraft.

c. Various equipment to be determined by system studies.

d. Asteroid docking and propulsion system.

e. Local transportation.

TABLE 18. ASTEROID RESOURCE COMPLEX (ARC)

Required Activities
• Personnel and cargo reception from EOT
• Personnel habitation
• Asteroid despinning
• Asteroid propulsion system docking
• Asteroid G& C systems docking
• Local movements
Program Subelements
• LEO-ARC transportation (P& C)
• ARC habitat base
• ARC equipment and operations
• ARC asteroid docking and propulsion
• ARC local transportation

B. Specific Program Requirements

A systematic search and ephemeris acquisition effort is required prior to any detailed technology planning. This search would concentrate on Earth orbit intercepting asteroids. Measurements on the physical characteristics and the chemical composition are required.

Principal methods and concepts of asteroid despin, capture, docking, propulsion, and control must be developed and major principles and guidelines for technically and economically accomplishing this task must be established.

The fractionalization of asteroid material for propulsion purposes (40 percent of asteroid) needs to be carefully explored.

Typical candidate asteroid sizes are:

Mass = 10^9 kg

Diameter = 150 m.

The previously mentioned specific program requirements of the ARC are listed in Table 19.

TABLE 19. SPECIFIC PROGRAM REQUIREMENTS

Asteroid Resources Complex (ARC) • Survey and ephemeris acquisition of near-Earth approaching asteroids • Establishment of physical and chemical characteristics • Asteroid fractionalization — Ability of capturing a 10^9 kg mass and a 150 m diameter — Ability of conversion of asteroid mass into propellant for insertion into SMF area

IV. DEMONSTRATION SYSTEMS

A. Objectives

The objective of the systems demonstration program is to convincingly demonstrate to the industrial and finance committees the capability to:

1. Construct economically competitive and technically sound large space systems in space.

2. Utilize extraterrestrial materials for their construction to the maximum extent.

3. To provide extraterrestrial materials at the quantity, rate, and quality required for large space systems construction.

4. To receive a specified expected input at a selected ground station on Earth from the constructed demonstration system. The input level necessary and sufficient for an acceptable demonstration must be defined by the recommended analytical studies.

The earliest demonstration will be focused about LEO space systems or modules primarily intended to demonstrate and qualify the basic technology and contributes one "GO" input into the decision structure for the second demonstration. The second demonstration (in GEO) embodies all of the elements and processes involved in the planned end product and should satisfy the economic concerns and need for confidence in the technical aspects of the prospective funding institutions.

The second demonstration may employ a considerable amount of simulated (terrestrially produced) lunar resources in its configuration. It would, however, be accompanied by a parallel (real) lunar resource acquisition and processing system which has contributed in part to the fabrication of the demonstration system and exhibits practical expansion up to the capacity needed for complete production of the end operational product. It should be recognized that in the use of nonterrestrial resources, a demonstration of this class must have instituted program growth to include those basic capabilities illustrated in Figure 5. This capability is basic to a following buildup (given a "GO" decision) to bring the end products into being and should, therefore, be compatible to such evolution.

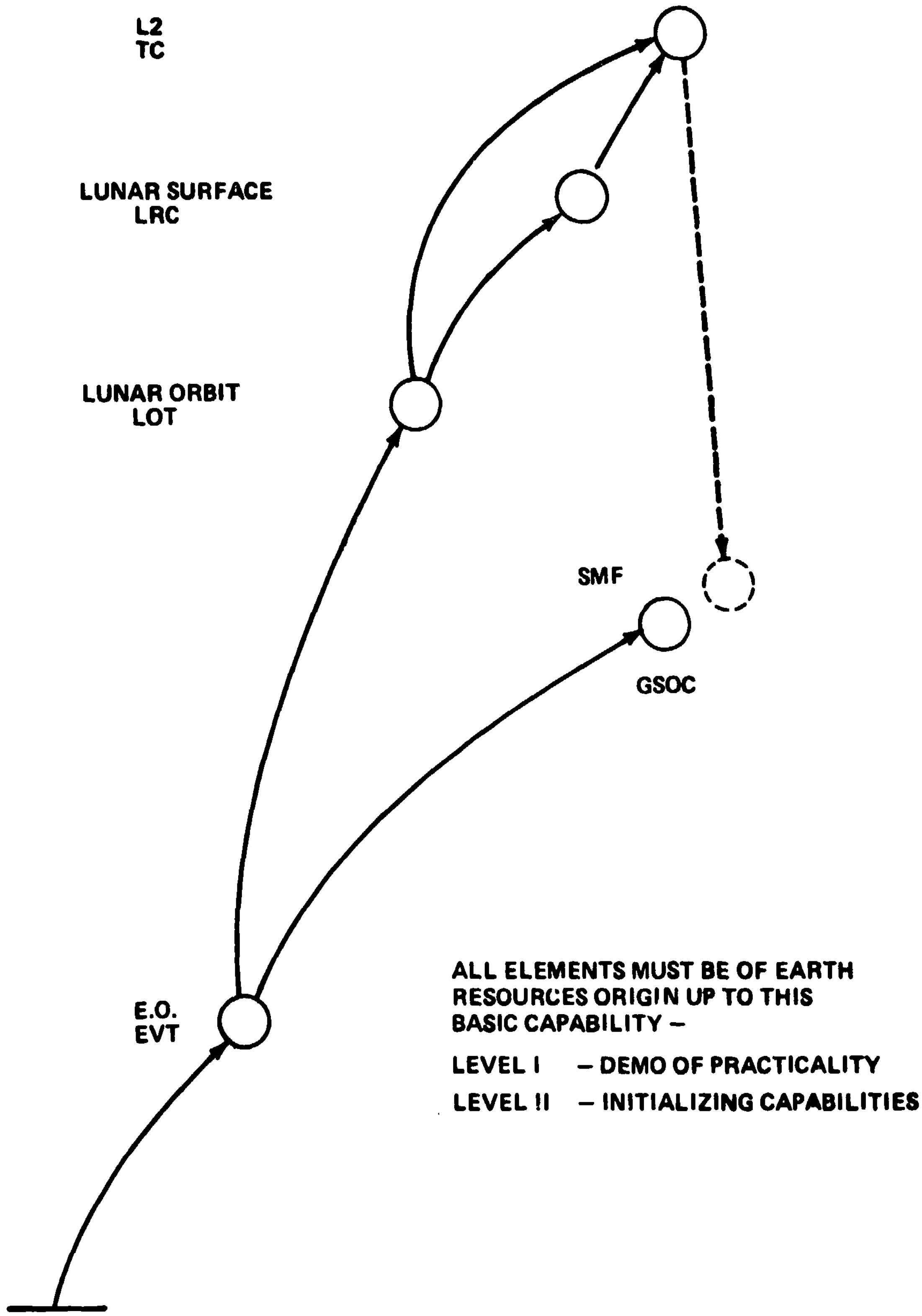

Figure 5. Basic capability.

Figure 6 draws attention to the need to recognize other possible major alternatives which can require pursuit of other critical technology. The figure indicates a need for the technological development of large space systems that is relatively independent of the means and resources for its operational construction, in concert with two independent paths of technology development relating to means of resources and implementation techniques (nonterrestrial versus terrestrial). Relative assessment and selection among these basic alternatives must occur before the basic scope of the demonstration program can be initiated.

The following requirements discussion deals only with the technology for the use of nonterrestrial materials in the development of large space systems.

B. Requirements

To clearly define the requirements of the system demonstration program, this phase must be considered in conjunction with preceding and subsequent phases. As shown in Section II, two major phases of a technology readiness effort are planned to occur prior to the demonstrations: (1) a component technology test bed program and (2) an exploration program. These must provide required information to decide on a system demonstration program leading toward a full operational capability demonstration of a prototype system.

While the component technology test bed program will exercise all critical technical aspects of systems and subsystems in subscale tests and demonstrations to develop a level of confidence in the concept feasibility, the system demonstration program will exercise all critical vital functions and processes in the required spatial locations necessary for subsequent full-scale operation of a prototype operation. The systems demonstration program, therefore, has the following general requirements:

1. Initiation of a program which develops and operates on the lunar surface and in space the complexes, facilities, and elements required to be able to initiate the access and use of extraterrestrial materials and begin the processing and production of the required large space system elements from which a demonstration system could readily be constructed and assembled.

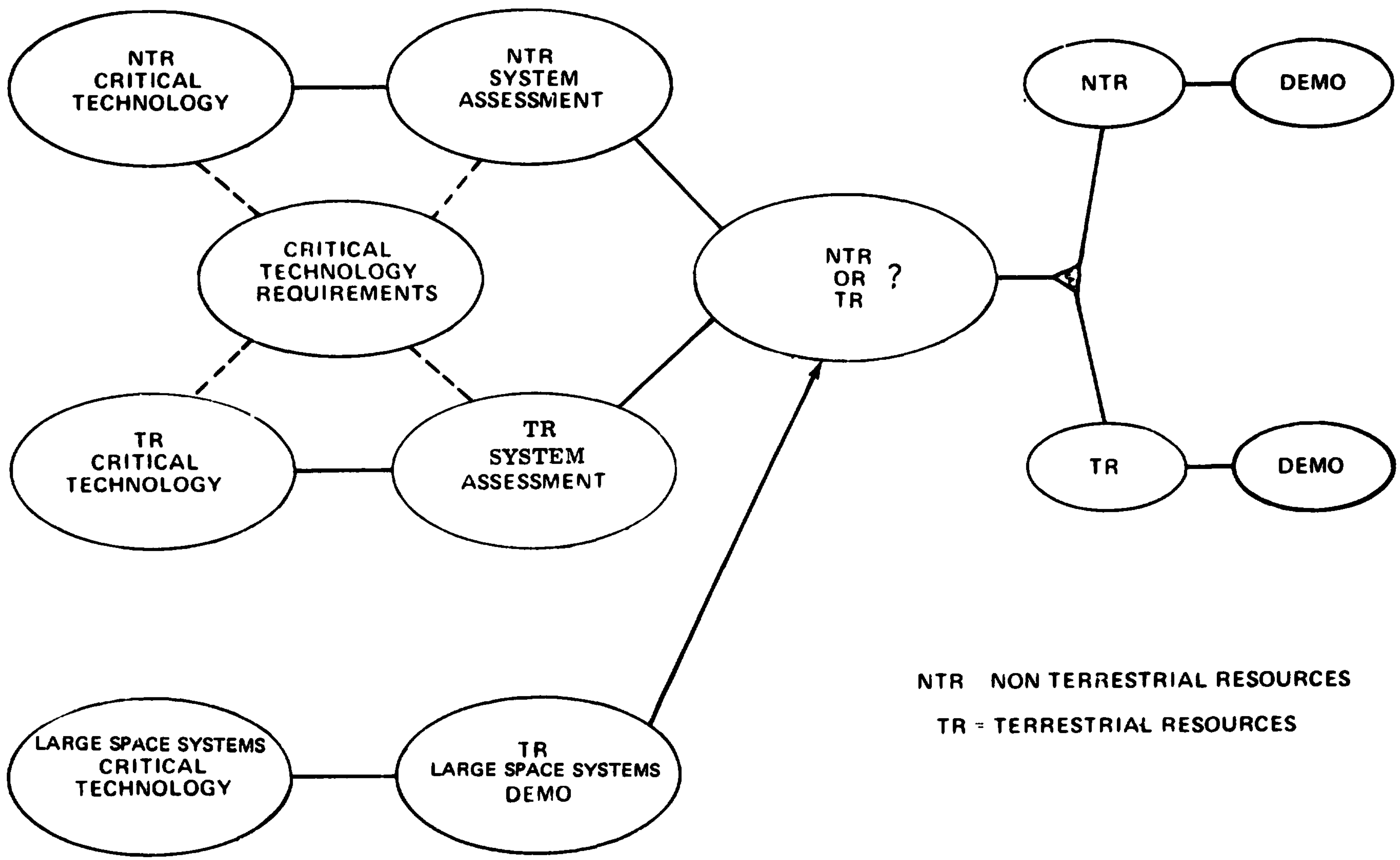

Figure 6. Logic flow for demonstration program.

2. Initiation of a program which develops and operates in GEO a pilot space system which has been fabricated, constructed, and assembled from simulated extraterrestrial materials of terrestrial origin.

After successfully implementing the previously listed initiating programs, the system demonstration program should lead (if the decision of program continuation were given) directly to a buildup program which would produce a large space system and extraterrestrial manufacturing prototype operational program.

This prototype operational demonstration of an operationally sized system will be the key to achieve the required confidence level for a required production rate program. This, then, would constitute the actual production program if the prototype operations are successful.

An unresolved key problem of the program buildup sequence is the decision to choose between the following demonstration options:

1. A buildup limited to produce a demonstration system of minimum acceptable capacity with a capability of subsequent expansion to an operational production cycle.

2. A buildup to produce a full-size operational prototype system with full operational production capability shortly thereafter.

Obviously, each option affects overall availability schedules for operational satellites and program costs. The overall R& D efforts, however, are not effected by these options.

C. Demonstration Systems

The demonstration systems presented in this section cover only the most critical areas and issues to be resolved and verified through systems demonstrations. It is merely the foundation upon which the final convincing step must rest: the prototype operational demonstration.

Any peculiar large space system related critical systems are excluded because it is assumed that these systems will be demonstrated as planned and studied within the respective large space system program. Only systems peculiar to the utilization of extraterrestrial resources are covered here, i.e., the lunar launcher, L2 payload interceptor ("mass catcher"), materials processing, manufacturing systems, lunar power systems, and long-term habitats.

All human and automated operations must be included in each system demonstration.

All required habitat and transportation systems for personnel and cargo must be included in each system demonstration.

The approach followed for overall systems demonstration is shown in Figure 7.

1. Lunar Launcher. The lunar launcher systems demonstration consists of the following:

a. Payload extraction and delivery

b. Payload packaging and transport

c. Lunar launcher operational installations

d. Lunar payload trajectory control

e. Lunar payload trajectory verification

f. Payload interceptor control verification.

Shortly after initial launcher demonstrations it will be necessary to initiate the L2 payload interceptor demonstration to absolutely verify the lunar payload trajectory and flight mechanics characteristics.

The assumed demonstration performance criteria are as follows:

a. Operating period — 30 days over 365 days

b. Launcher throughput rate (periodic) — 4×10^6 kg/day.

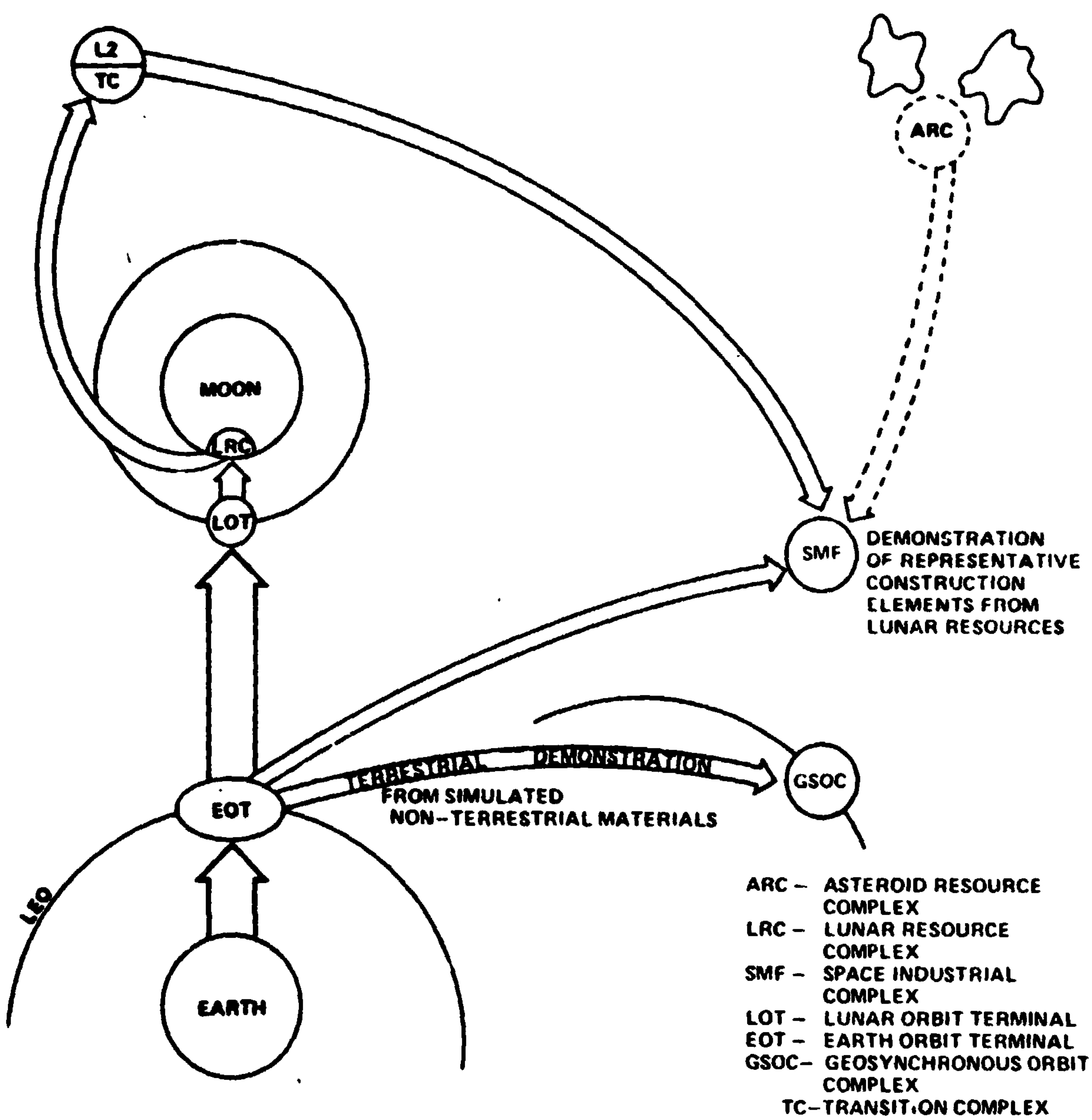

Figure 7. Nonterrestrial construction demonstration model for large space systems.

2. L2 Payload Interceptor ("Mass Catcher"). The L2 payload interceptor systems demonstration consists of the following:

a. Lunar launch control receiver

b. An interceptor

c. Interceptor attitude and position control systems

d. Interceptor sequencing command center

e. Interceptor mass control systems

f. Interceptor propulsion and power systems

g. Interceptor guidance and flight control system

h. Interceptor data and communication system.

This systems demonstration must be initiated shortly after the lunar launcher demonstration activation and be performed in conjunction with it.

The assumed demonstration performance criteria are as follows:

a. Operating period — 30 days over 300 days

b. Mass flow (periodic) — 4×10^6 kg/day.

3. Materials Processing and Manufacturing Systems. This systems demonstration can be performed to a large extent with simulated lunar materials. Actual lunar material processing will be done based on the then limited quantities available and the need for actual lunar material where simulation falls short in providing acceptable characteristics.

Since the purpose of SMF is the production of a large space system, the demonstration has to produce all critical and significant system components and elements required except those that would be delivered from Earth. This systems demonstration consists of the following operations:

a. Raw materials processing

b. Manufacturing of system components from processed raw material

c. Fabrication and construction of system elements from manufactured components

d. Quality assurance, accounting, and storage of products.

The assumed demonstration performance criteria are as follows:

a. Operating period — 30 days over 300 days

b. Materials processing — 4×10^6 kg/day

c. Product flow (periodic) — 1.5×10^6 kg/day.

4. Lunar Power Systems. Lunar power systems demonstrations must be performed in conjunction with the lunar launcher demonstration and the associated operations. This systems demonstration consists of the following:

a. Base power plant

b. Peak power plant

c. Waste heat radiation system

d. Utility interface and control system

e. Distribution system.

The assumed demonstration performance criteria are as follows:

a. Operating period — 30 days over 365 days

b. Power capacity — 50 MW.

5. Long-Term Habitats. This systems demonstration consists of simultaneous habitat demonstrations at the following space locations:

a. Earth Orbital Terminal (EOT)

b. Lunar Orbital Terminal (LOT)

c. Lunar Resources Complex (LRC)

d. Transition Complex Spacecraft (TC)

e. Space Manufacturing Facility (SMF).

Each demonstration will include the following subsystems:

a. Life support and ecological systems

b. Structures

c. Attitude control and stationkeeping (except LRC habitat)

d. Power supplies

e. Thermal control.

The assumed demonstration performance criteria are as follows:

a. Operating life — 30 years

b. Population — EOT and LRC: 50 to 100

LOT: 5 to 10

TC: 5

SMF: < 6000.

REFERENCES

1. Space Settlements. A Design Study NASA SP-413, 1975, Publishing Date 1977.

2. A System Design for a Prototype Space Colony. A Student Project in System Engineering, M.I.T. and W. Fellarlar Foundation, Inc., 1976.

3. O' Leary, Brian: Mining the Apollo and Amor Asteroids. Princeton University Press, Princeton, New Jersey, 1977.

4. Space Manufacturing From Non-Terrestrial Materials. NASA-Ames OAST Study, 1976.

5. Space Manufacturing Facilities. Space Colonies, Proceedings of the Princeton/ AIAA/ NASA Conference, 1975.

6. 1977 Ames Space Settlements and Industrialization Study. Preliminary papers and discussions.

APPROVAL

IN-SPACE PRODUCTION OF LARGE SPACE SYSTEMS FROM EXTRATERRESTRIAL MATERIALS – A PROGRAM IMPLEMENTATION MODEL

By Georg F. von Tiesenhausen

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

H. P. GIEROW
Director, Advanced Systems Office

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